A Laser Look inside Planets

TRADITIONAL lasers, gas guns, and other dynamic high-pressure testing methods launch an instantaneous shock into a target, resulting in rapid heating, which at high pressures causes the material to melt. A new technique called laser-driven ramp compression zaps the material with a carefully tailored laser shot. Laser-driven ramping can achieve high states of compression while simultaneously keeping the target material relatively cool so scientists can examine the material under high pressures. The "loading" time of laser ramp compression is just a few nanoseconds, or 10 times faster than that of the fastest alternative.

Under extremely high pressures, the target material may remain in its initial phase, or it may change from a solid to a liquid or from one solid phase to another. To date, laser-ramp-compression experiments have achieved pressures up to 1,400 gigapascals (GPa), or 1.4×10^{12} pascals. For reference, ambient air pressure is 100,000 pascals, and the pressure at the center of Earth is about 350 GPa.

Shock experimental methods reveal a snapshot of part of a phase transition. Ramp compression offers the first continuous view of the phase transition and thus will help scientists better understand the physics of solids at extreme conditions. "We now can see how quickly the transition mechanisms happen," says physicist Ray Smith, who leads the ramp-compression research team in Livermore's Physical and Life Sciences Directorate.

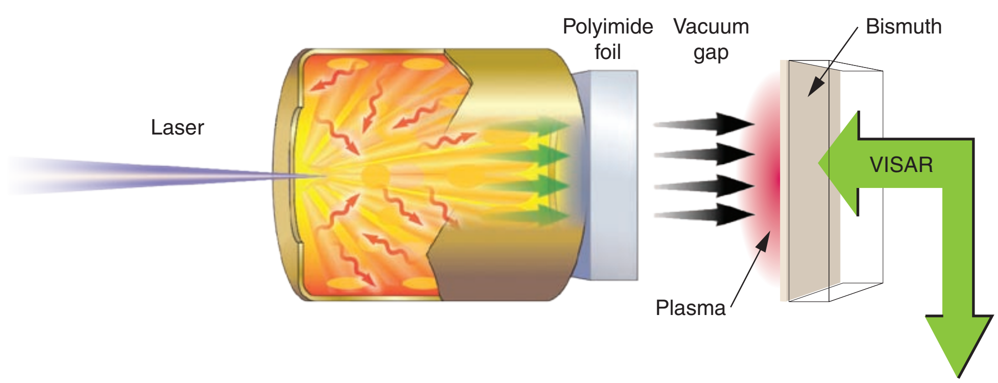
Because of these unique attributes, ramp compression is the only tool that will allow scientists to examine the interior structure of exoplanets—planets in other solar systems—that are similar to but larger than Earth. More than 250 exoplanets have been discovered since 1995, but most are huge gas giants similar to Jupiter and Saturn. In the last few years, detection and survey methods have improved such that smaller exoplanets and ones closer to their parent star can be found. While our solar system contains only small rocky planets and gas giants, recent discoveries indicate that other solar systems contain a new family of terrestrial planets more massive than Earth but smaller than the gas giants.

These so-called super-Earth planets range from 1 to 10 times the mass of Earth, with pressures at their core from 3,000 to 5,000 GPa. Although ramp-compression experiments have yet to achieve the high pressures at a planet's core, they can re-create the phase transitions occurring well beneath an exoplanet's surface. Scientists can thus use this laser method to test various planetary hypotheses, such as whether Uranus has a solid diamond core.

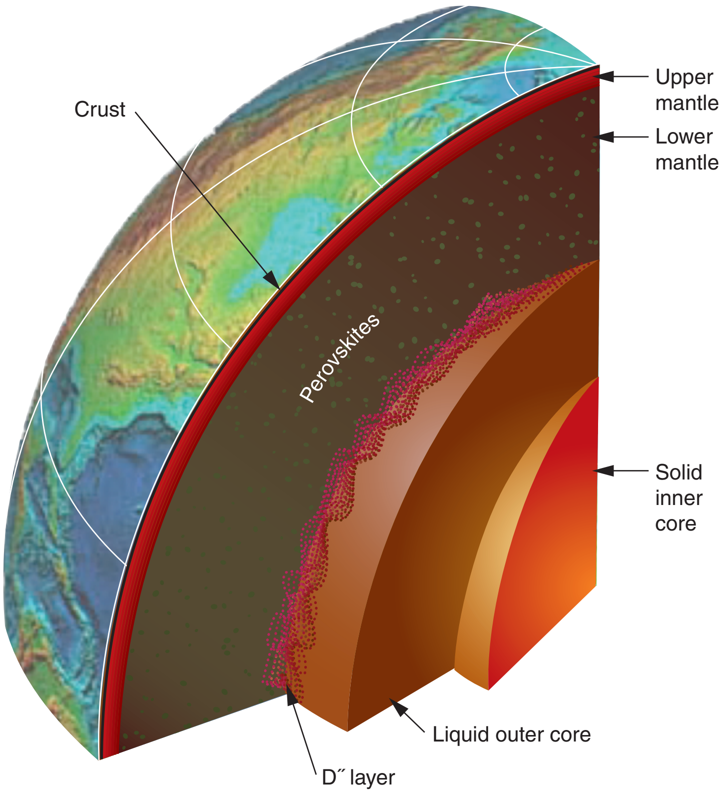
Ramping Up the Method

In 2005, Livermore physicist Marina Bastea performed the first experiments to ramp-compress bismuth. Those experiments were conducted on the Z machine, the x-ray source at Sandia National Laboratories in New Mexico, and the compression rates were about 10 times slower than the rate obtained in subsequent experiments with Livermore's Janus laser.

Since then, Smith's team has developed the techniques and diagnostic tools essential for routine high-pressure ramp-compression experiments. In 2007, the team used one beam of the Janus laser to generate a 150- to 200-joule pulse that strikes a polyimide foil and rarefies it. The polyimide crosses the vacuum gap and hits the bismuth sample, launching a ramp-compression



In ramp-compression experiments on Livermore's Janus laser, the laser beam directs a pulse toward a polyimide foil. The polyimide crosses the vacuum gap and hits the bismuth sample, launching a ramp-compression wave with peak pressure between 8 and 11 gigapascals. A diagnostic called VISAR (Velocity Interferometer System for Any Reflector) records the time history of the compression wave.



Using seismic-wave data recorded during earthquakes and other geologic disturbances, scientists have determined the makeup of Earth's interior. Ramp-compression experiments will offer yet more clues about deep-Earth conditions.

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Bismuth samples are preheated to a range of temperatures, which enables access to different regions of the pressure–temperature continuum and provides insights into the phase-transformation mechanisms. "The pressure at which the phase transition occurs shows a deviation from the crystal's equilibrium value," says Smith. "For the first time, we can see the very brief timescale during which the crystal transforms to a new structural phase."

Subsequent experiments led by Livermore physicist Dave Bradley compressed diamond, a solid phase of carbon, using the higher energy OMEGA laser at the University of Rochester's Laboratory for Laser Energetics. These experiments yielded the highest ramp-compression pressures ever reported, 1,400 GPa, as well as the highest-pressure solid equation-of-state data. Data for pressure versus density indicate that the diamond phase is stable with significant material strength up to at least 800 GPa.

Data Still to Come

The research team has received funding from Livermore's Laboratory Directed Research and Development Program and is now working on a collaborative project to perform more ramp-compression experiments at OMEGA. In addition to Smith and Bastea, this effort includes Laboratory researchers Jon Eggert, Pete Celliers, David Braun, and Ryan Rygg as well as scientists from Washington State University, Princeton University, Carnegie Institution for Science, University of Rochester, and University of California at Berkeley. These new measurements will more carefully define the phase boundaries, kinetics, and thermodynamic properties under deep-Earth conditions, which will help scientists better understand the structure and composition of planetary interiors.

The first shots will compress iron up to about 500 GPa. The team will also examine silica, which serves as an archetype for the dense, highly coordinated silicates that make up planetary interiors. Enstatite, another common mineral in Earth's mantle, transforms to perovskite, the most abundant phase in Earth's vast lower mantle. A series of OMEGA experiments will probe the expected enstatite–perovskite phase change, the perovskite–postperovskite phase change, and any as-yet-unknown phase changes above 200 GPa. The primary diagnostic tools, VISAR and x-ray diffraction, will provide information on the crystal structure of the new phases.

In September, some of the same partners will collaborate on the first ramp-compression experiments at the National Ignition Facility (NIF), the world's most energetic laser system. The first material to be subjected to NIF's high-power beams will be tantalum, which will be compressed to 500 GPa to examine its equation of state. Iron, other heavy metals, and diamond will also be on the receiving end of 96 NIF beams. Says Gilbert (Rip) Collins, a coleader for the NIF experiments, "NIF will enable us to examine the evolution, structure, and internal chemistry of solar and extrasolar planets."

—Katie Walter

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